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THE GRAIN SIZE OF STEEL

By J. R. VILELLA

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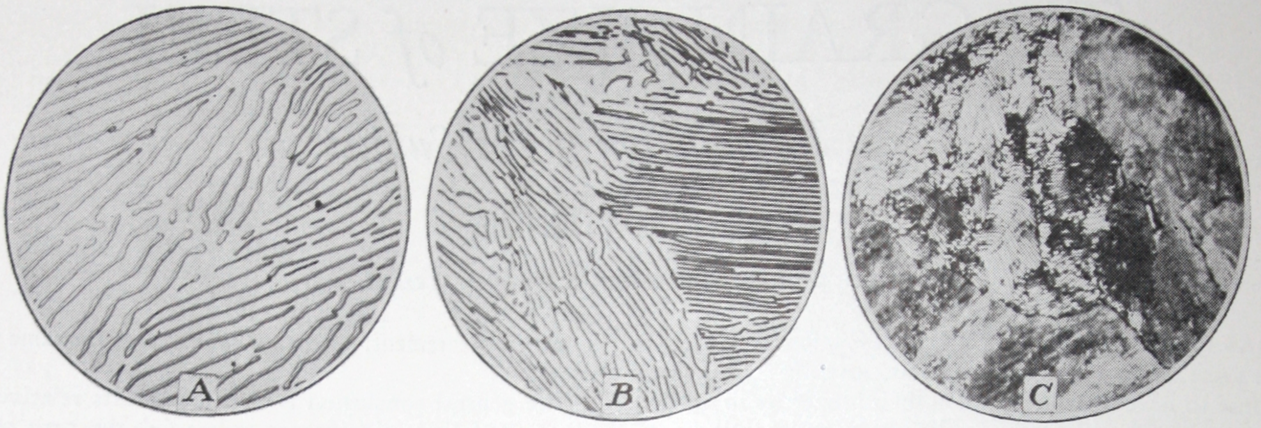

FIG. 1 THESE ARE PEARLITE STRUCTURES IN 0.85 C STEEL; THE MAIN DIFFERENCE BETWEEN THEM IS THE SPACING OF THE LAMELLAE; THE WHITE GROUND MASS IS FERRITE AND THE GRAY (*A*) OR BLACK STRIATIONS (*B* AND *C*) ARE IRON CARBIDE, ×2500

Figure	Cooling rate	Hardness Rockwell C	 Brinell
A	Very slow	5	163
B	Slow	15	207
C	Moderately fast	38	363

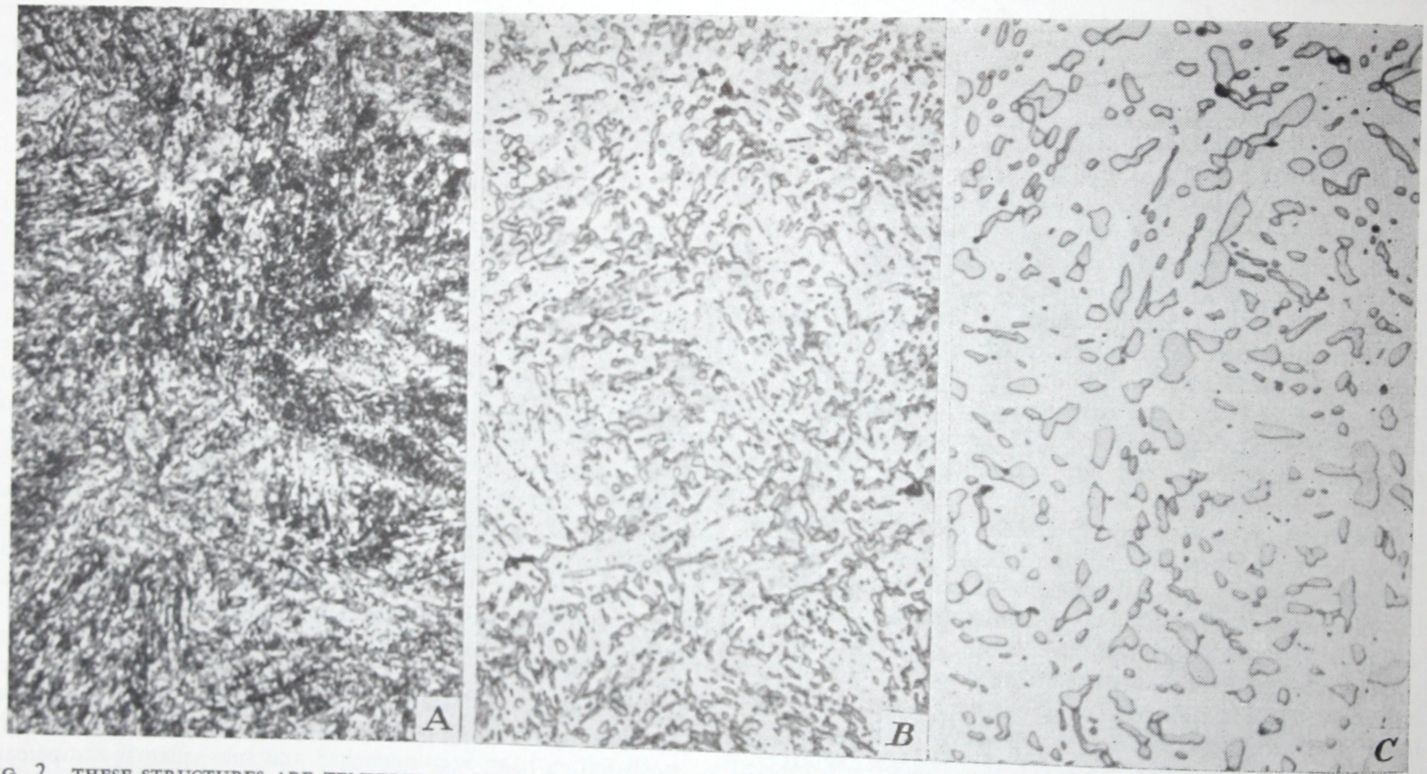

FIG. 2 THESE STRUCTURES ARE TEMPERED MARTENSITE OR SPHEROIDIZED CARBIDES, ×2000. THEY DIFFER PRIMARILY IN THE COARSENESS OF THE CARBIDE PARTICLES. THE WHITE BACKGROUND IS FERRITE

(They were all quenched in water and tempered as follows: *A*, tempered 0.85 C steel, 1 hr at 1020 F (550 C); *B*, tempered 0.89 C steel, 5 min at 1200 F (650 C); *C*, tempered 0.95 C steel, 24 hr at 1200 F (650 C).)

always carried out at temperatures below about 1330 F (720 C), the lower limit of the transformation range.

The important fact to remember is that at ordinary temperatures the ferrite ground mass and the iron-carbide particles exist as separate phases generally identifiable under the microscope. The separate existence of these two characteristic constituents of steel at ordinary temperatures is the result of the inability of ferrite to hold more than a mere trace of iron carbide in true solution. However, in steels which have been quenched to attain maximum hardness (but not tempered), the carbide particles are not visible at any available magnification; the reason for this is that either the carbide particles are too small for microscopic resolution or the iron carbide is actually in unstable (supersaturated) solution in the iron matrix. The structure of a steel thus quenched is acicular and is known as martensite; its appearance under the microscope is illustrated in Fig. 3. Martensite is the hardest, strongest, and least ductile form of steel. While the actual state of the carbon in martensite is uncertain and while it appears that at room temperature martensite is capable of remaining unchanged indefinitely, it begins to decompose slowly into ferrite and spheroids of iron carbide when it is heated to as low a temperature as that of boiling water, and this tempering process goes on faster as the temperature increases.

When a piece of steel is heated, irrespective of its condition at room temperature or of its carbon content if more than about 0.04 per cent, it begins to undergo a radical transformation when a temperature of approximately 1335 F (725 C) is reached.

Up to this temperature, no part of the ground mass is able to dissolve more than 0.04 per cent carbon, but just a few degrees higher those parts of the ground mass in which carbide particles are present acquire suddenly the power to dissolve as much as 0.75 per cent carbon. This sudden change is a manifestation of a profound alteration in the nature of the metal, which the metallurgist recognizes as the appearance of a totally different crystalline form of iron called austenite. Austenite is a solid solution of carbon in the high-temperature crystalline form of iron. The temperature at which the change to austenite occurs is called the *transformation* or, less aptly, the *critical* temperature.

The beginning of this transformation on heating occurs always at practically the same temperature in all plain carbon steels, but the temperature at which the metal becomes 100 per cent austenite varies with the carbon content. It is lowest (1330–1340 F) in a steel of about 0.75 per cent carbon—the so-called eutectoid composition—but rises gradually as the carbon is either less or more than 0.75 per cent. It is for this reason that the heat-treating temperature recommended for, let us say, a 0.20 per cent carbon steel is higher than that for a 0.75 per cent carbon steel.

As is to be expected, the reverse of this transformation takes place on cooling; that is, when austenite is cooled below the transformation temperature range it becomes unstable and eventually transforms to a mixture of ferrite and carbide, the latter being precipitated because the new ferrite phase is unable to hold all the carbon in solution. It must be noted, however, that the transformation on cooling occurs at a lower temperature than on heating. In fact, austenite may transform to ferrite and carbide at any temperature from 1330–1340 F down to approximately 1000 F (540 C), depending on the rate at which the austenite is actually cooling. It may even not transform until room temperature is reached if the cooling rate is sufficiently fast, but a transformation at temperatures between about 1000 F and room temperature can scarcely occur when the cooling medium is at or below room temperature. For an exposition of the modern views on the rate of transformation of austenite and its consequences, the reader is referred to the Bibliography (1, 2, 3).[4] The point to remember is that austenite is really stable only at temperatures above about 1330 F; therefore, it is not present in slowly cooled steels. An appreciable amount may remain untransformed in a quenched high-carbon steel but will transform if the steel is either reheated to about 600 F and held at that temperature for a sufficient length of time, or if it is cooled below room temperature. In general, the lower the temperature the less the amount of retained austenite.

Crystals and Grains. Steel, like all solid metals, is a crystalline aggregate, and within each crystal, its atoms are spaced in the same orderly pattern. This orderly arrangement of the atoms is the fundamental difference between crystalline and amorphous solids; in the latter the atoms are distributed more or less haphazardly. In ferrite, the spacing of the atoms is represented by a cubic array in which there is one atom at each corner of the unit cube and one at the center; this "body-centered cubic" array of the iron atoms is known as alpha iron, and a solid solution in which alpha iron is the solvent is called ferrite. During the transformation from ferrite to austenite on heating, a rearrangement of the atoms takes place, and their new spacing is represented by a cubic array in which there is one atom at each corner and one at the center of each face of the unit cube. This arrangement is referred to as "face-centered cubic" or gamma iron. When gamma iron is the solvent, the solid solution is known as austenite.

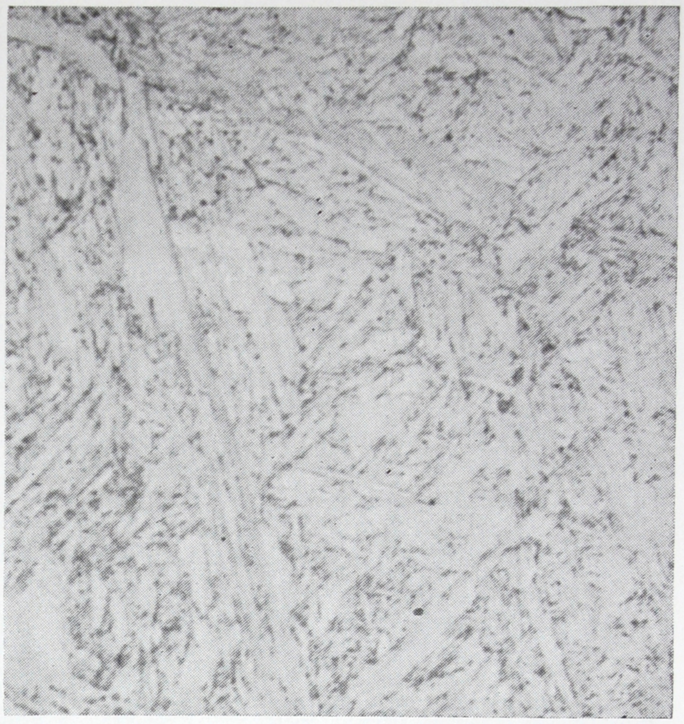

FIG. 3 MARTENSITE STRUCTURE IN 0.85 C STEEL, ×2500. ROCKWELL C HARDNESS IS 66, BRINELL 745

In spite of the fact that steel is crystalline at all temperatures below its melting point and under all conditions of mechanical and thermal treatment, its structure under the microscope is not made up of well-formed geometrical crystals, such as cubes or octahedra, but rather of irregularly shaped portions of metal, frequently bounded by curved surfaces, which are known as grains. In each of these grains there is a single and continuous orientation of the array of atoms, but the orientation always varies from grain to grain.

Grains of the same composition and atomic arrangement are attacked by chemical substances at different rates, depending on the orientation initially presented to the corroding medium. This fact enables the metallographer to reveal the confines of each grain, even in the purest metals, by suitable metallographic etching.

The original grains form first when the liquid steel freezes in the ingot mold. Since freezing, or solidification by crystallization, begins at many places simultaneously, the growth of any one crystalline grain is soon interrupted by the growth of its neighbors; consequently, none ever attains either a very large size or the symmetrical shapes usually observed in those cases where each crystal can grow uninfluenced by others. These grains, nevertheless, are much larger than those present later when the steel is wrought. While the principal object of the mechanical hot working of steel is to shape it into useful objects, it also serves to break up the original ingot grains into the much finer ones generally found in rolled or forged sections. It is well to note here that hot working is generally carried out while the steel is austenitic, and cold working when it is ferritic.

GRAINS AND THEIR CHARACTERISTICS

For the purpose of this review, the most important facts pertaining to the grains of steel and their growth are the following:

1 There are in steel only two kinds of grains, the size of which is recognized as influencing its properties—austenite grains and, secondarily, ferrite grains.

2 Regardless of the size of the grains at room temperature,

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[4] Numbers in parentheses refer to the Bibliography at the end of the paper.

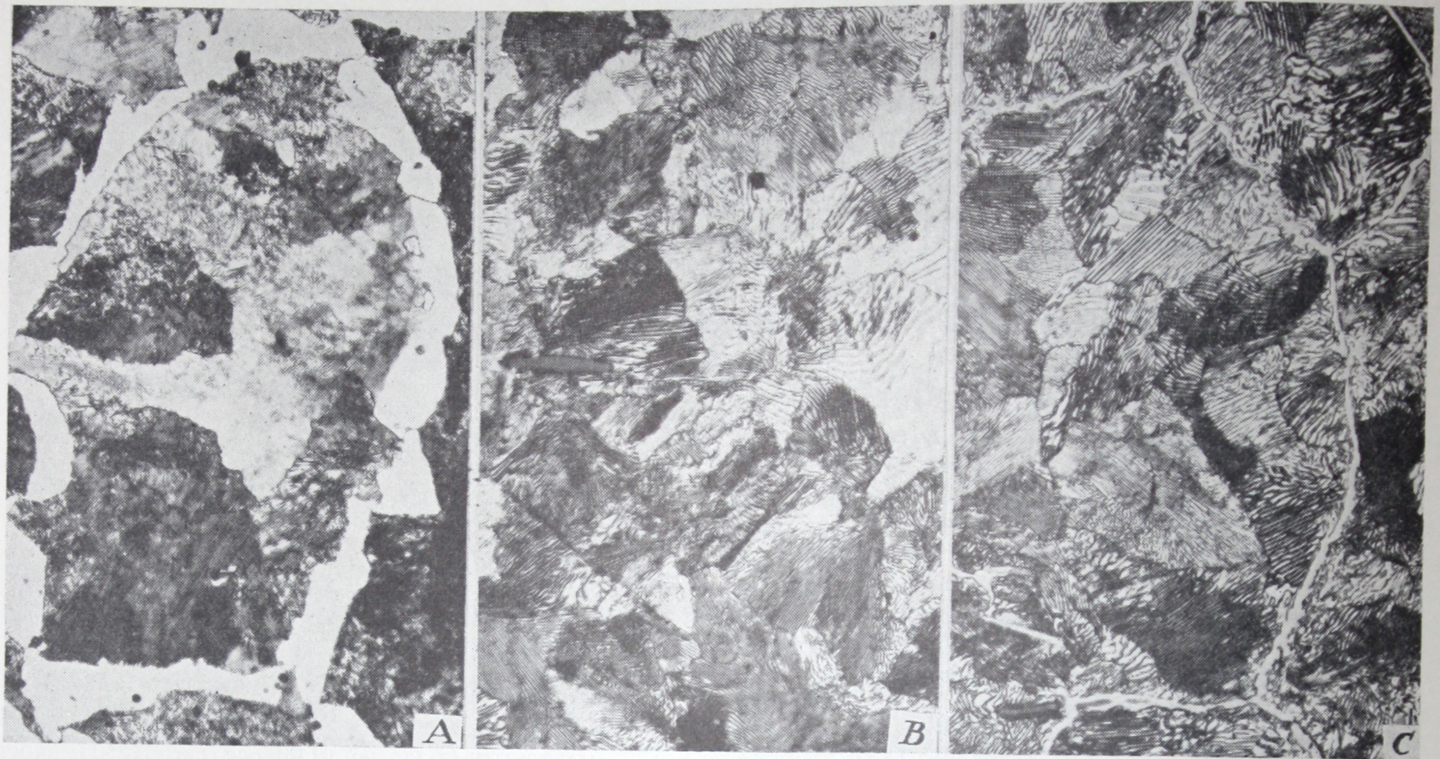

FIG. 4 TYPES OF GRAINS PRESENT IN NORMALIZED OR ANNEALED STEELS OF DIFFERENT CARBON CONTENT, ×500

(In Fig. *A*, 0.40 C steel, the austenite grains are marked out by white ferrite network; the ferrite network itself is made up of ferrite grains; the pearlite areas within the network are made up of pearlite colonies. Fig. *B* is 0.85 C steel—only the pearlite colonies are visible and these do not indicate anything about austenite grain size. Fig. *C* is 1.20 C steel—the austenite grains are marked out by network of iron carbide but within this network the pearlite colonies are visible.)

when steel is heated above its transformation temperature the newly formed austenite grains are initially small.

3 During heating within the stable austenite range, the higher the temperature and the longer the time at that temperature, the larger the austenite grains tend to become.

4 The size attained by the austenite grains at the maximum temperature is not altered by variation in the rate of cooling from that temperature under all ordinary conditions of cooling.

5 Although steels at room temperature are generally ferritic, it is possible, nevertheless, to detect at room temperature the austenite grain pattern which existed at the maximum temperature in the austenite range reached during the last heating period.

6 In the ferritic range (that is, at temperatures below the transformation range of the steel), the tendency of the ferrite grains to grow with increasing temperature is comparatively small, except after they have been deformed by cold work to a so-called critical amount.

7 In general, the faster the cooling rate from the austenitic range, the smaller the ferrite grains; while for the same cooling rate, the larger the austenite grains the larger the ferrite grains.

A more detailed discussion of each of the foregoing statements follows:

1 *The Grain Systems of Steel.* Actually, three types of grain patterns are recognizable in steel, but only two, ferrite and austenite, are generally considered of technical importance. The third type, which is observed only within the pearlite areas, is occasionally referred to as "pearlite colonies." So far no correlation has been found between the size of these colonies and the mechanical properties of steel. The three types are illustrated in Figs. 4*A*, 4*B*, and 4*C*. Note in Fig. 4*A*, illustrating the structure of a 0.40 per cent carbon steel air-cooled from 1600 F, that the white areas of ferrite form a network; this network delineates the antecedent austenite grain pattern. Observe also that the ferrite areas are themselves made up of smaller grains; these are ferrite grains. Now, turning attention to the darker pearlite areas, observe that within the pearlite area surrounded by ferrite there are rather well-defined subdivisions; these are the so-called pearlite colonies.

Fig. 4*B* represents the structure of a normalized 0.85 per cent carbon steel. Since a steel of this composition contains no free ferrite, that is, it is entirely pearlitic, there is nothing with which to outline the austenite grains; therefore, they are not detectable. This apparent "grain" structure is again what we refer to as pearlite colonies.

Fig. 4*C* is the structure of 1.20 per cent carbon steel, furnace-cooled from 1700 F. Two systems of grains are clearly visible; the larger one delineated by a network of iron carbide is the former austenite grain system; the subdivisions of the pearlite areas are, again, the pearlite colonies.

So far metallurgists have paid little attention, if any, to the possible influence of the size of these pearlite colonies upon the properties of the metal. The conditions which appear to affect their size will be referred to later.

2 *The Austenite Grain Size at the Transformation Temperature.* The control of the size of the austenite grains by heat-treatment depends on two facts: (*a*) When ferrite and iron carbide dissolve to form austenite, the size of the austenite grains at birth is small; and (*b*) these small grains tend to grow, and more rapidly the higher the temperature. The growth of the austenite grains with increasing temperature is demonstrated in Figs. 5*A* and 5*B*, representing two specimens of the same 0.35 per cent carbon steel heated 10 min at 1600 F and 2000 F, respectively, and cooled in an appropriate manner to reveal the size of the austenite grains existing at the heating temperature. This is discussed later under "gradient-quench method."

While the size of the austenite grains at birth is small, the size attained just above the transformation range is not always the same; it appears to be influenced by several factors, among

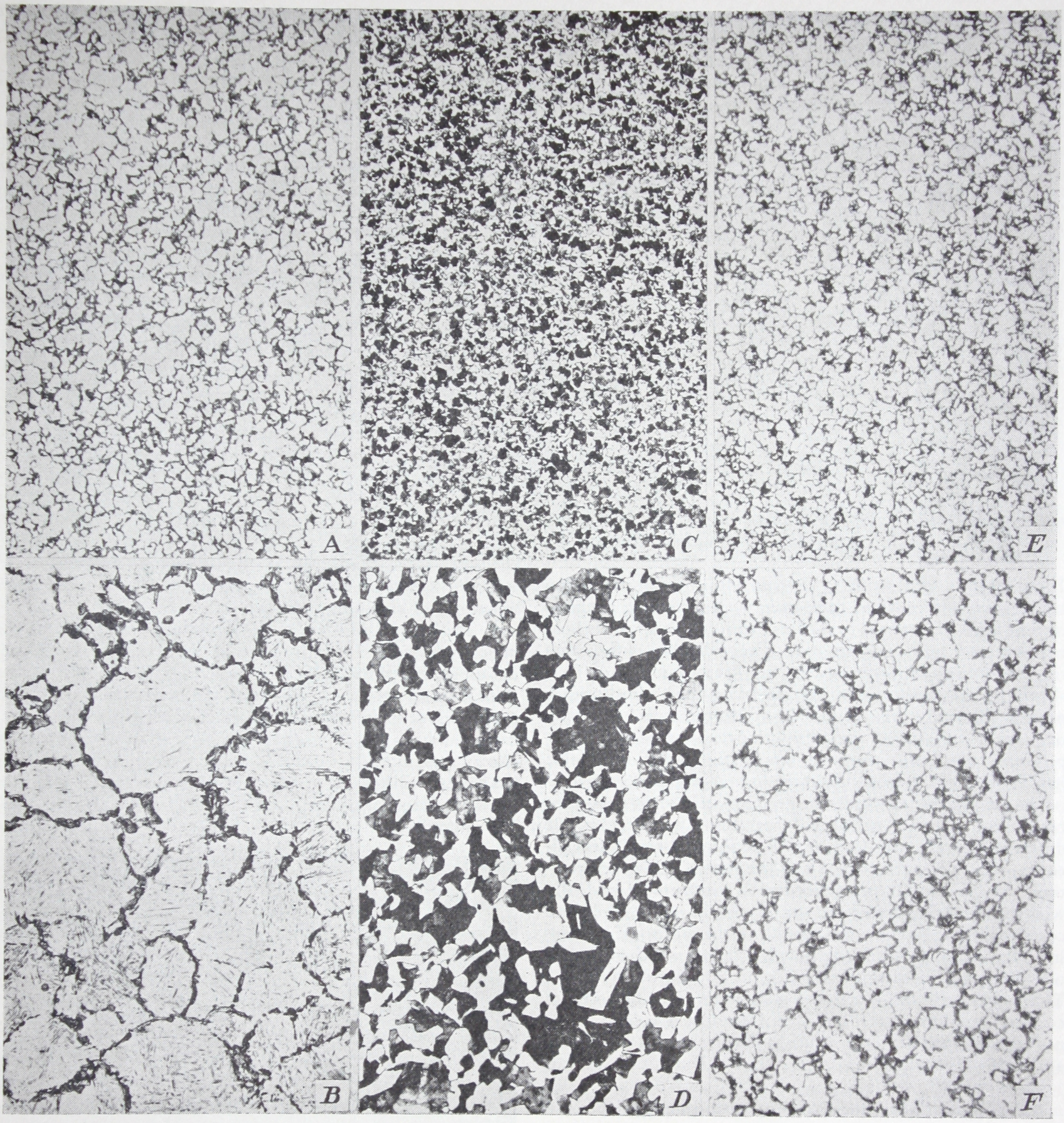

FIG. 5 STRUCTURES OF 0.35 C STEEL

(Figs. *A* and *B* were heated 10 min at 1600 F (870 C) and 2000 F (1095 C), respectively, and cooled in an appropriate manner (gradient-quenched) to reveal the austenite grain size; they illustrate the growth of austenite grains with increasing temperature. Figs. *C* and *D* are, respectively, the structures obtained in two specimens similar to *A* and *B* and similarly heated but cooled slowly with the furnace; the structures consist of pearlite areas (dark) in a ferrite matrix (white). Figs. *E* and *F* show the austenite grain size obtained when specimens *C* and *D*, respectively, were reheated 10 min at 1500 F (815 C) and gradient-quenched; note that coarser austenite grains were obtained from the specimen which originally had a coarser distribution of the pearlite and ferrite areas.)

which is the microstructure of the steel prior to heating. Figs. 5*C* and 5*D* represent two specimens from the same 0.35 per cent carbon steel, heated 10 min at 1600 F and 2000 F, respectively, and cooled slowly with the furnace. Note that the higher temperature produced a coarser distribution of the ferrite and pearlite constituents. These same two specimens were then reheated 10 min at 1500 F (just above the transformation range of this steel) and again cooled to reveal the austenite grain size established at 1500 F. This is shown in Fig. 5*E* and 5*F*. Note that the austenite grain size is somewhat coarser in the specimen which had originally larger ferrite and pearlite areas.

3 *Coarse- and Fine-Grained Steels.* The fact that austenite grains grow with increasing temperature was demonstrated by the previous experiment and shown in Figs. 5*A* and 5*B*, but it must not be inferred that all steels behave alike. The truth is

that in some steels grain growth begins as soon as austenite appears while in others no appreciable growth takes place in a reasonable time until the austenite is heated several hundred degrees higher. The mode of growth of the austenite grains in these two types of steel is illustrated schematically in Fig. 6.

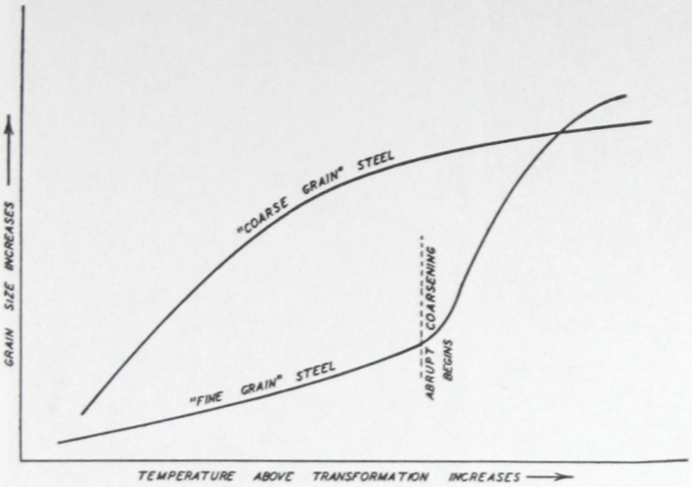

FIG. 6 TREND OF GROWTH OF AUSTENITE GRAINS WITH INCREASING TEMPERATURE IN COARSE- AND FINE-GRAINED STEELS

Those steels which begin to coarsen near the transformation temperature and continue to coarsen with increasing temperature are generally referred to as coarse-grained steels, while those which resist grain growth over a considerable temperature range are known as fine-grained steels. The most important fact, shown by these curves, is that a so-called fine-grained steel is not one immune to grain growth at all temperatures but simply one capable of resisting grain growth over a considerable temperature range, when held at temperature for a reasonable length of time such as is customary in heat-treating practice.

The temperature at which fine-grained steels begin to coarsen rapidly is generally called the coarsening temperature. It differs in different steels and, as will be shown later, is dependent also on the length of time that the steel is held at temperature. The so-called coarse-grained steels coarsen more gradually with increasing temperature, and do not have a well-defined coarsening temperature. In general, in the process of coarsening, all fine-grained steels go through a stage in which more than one grain size is distinctly visible, as illustrated in Fig. 7. This mixed grain size is merely a stage in the normal process of coarsening of any fine-grained steel; whether it is observed or not depends upon the temperature to which the steel was heated and the time at which it was held there. For this reason it is preferable to avoid the use of the term "duplexing" to denote a steel in which mixed grain sizes have been observed; moreover, the term "duplexed" is confusing for it has long been used to designate steels made by a combination of the Bessemer and either the open-hearth or electric processes.

TABLE 1 EFFECT ON GRAIN SIZE OF TIME AT TEMPERATURE

Temperature, F	Time at temperature, min	Austenite grain-size number[a]
1425	20	7
	45	7
	180	90% 7; 10% 3
1625	20	7
	60	75% 7; 25% 4
	180	75% 7; 25% 3
	300	25% 7; 75% 2
1625	20	7
	45	70% 7; 30% 4
	180	5% 7; 95% 3

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[a] In this table a small number indicates a coarse austenite grain size, that is, No. 2 grain size is coarser than a No. 7 grain size. This is discussed in more detail later in this paper.

In general the austenite grains grow at a diminishing rate as the time at temperature is prolonged; consequently growth practically ceases, or at least becomes very slow, after a certain size is attained. Data covering a long period of time are not available but those given in Table 1 indicate the trend.

The effect of time at temperature on the size of the austenite grains is also shown in Figs. 8*A*, 8*B*, and 8*C*. The rate of growth of the austenite grains is slowest near the transformation range, but increases gradually and continuously with temperature. In the so-called fine-grained steels, however, there is for each steel a fairly definite minimum temperature above which the grains grow quite fast when the steel is held at that temperature.

4 *Effect of Cooling Rate on the Austenite Grain Size.* Whatever size the austenite grains attain at the maximum temperature, that size remains unchanged as the steel cools to room temperature, provided, of course, the cooling rate is not so exceedingly slow that the metal stays near the maximum temperatures for a long time, in which case some growth may occur. In practice, it is safe to consider the austenite grain size observed in the steel as that attained at the maximum temperature to which it was last heated; this assumption is made in all determinations of austenite grain size.

5 *Methods of Ascertaining the Austenite Grain Size.* In the majority of cases when the metallurgist speaks of grain size, unless ferrite is specified, he is referring to the size of the prior austenite grains, for these are the grains influencing such properties as hardenability, toughness, and, to some extent, machinability. Since it is not convenient to ascertain their size by examination at elevated temperatures, the metallurgist has devised methods of marking out the grains at high temperature for subsequent estimation of their size at room temperature. The unfortunate part of this is that one of the methods

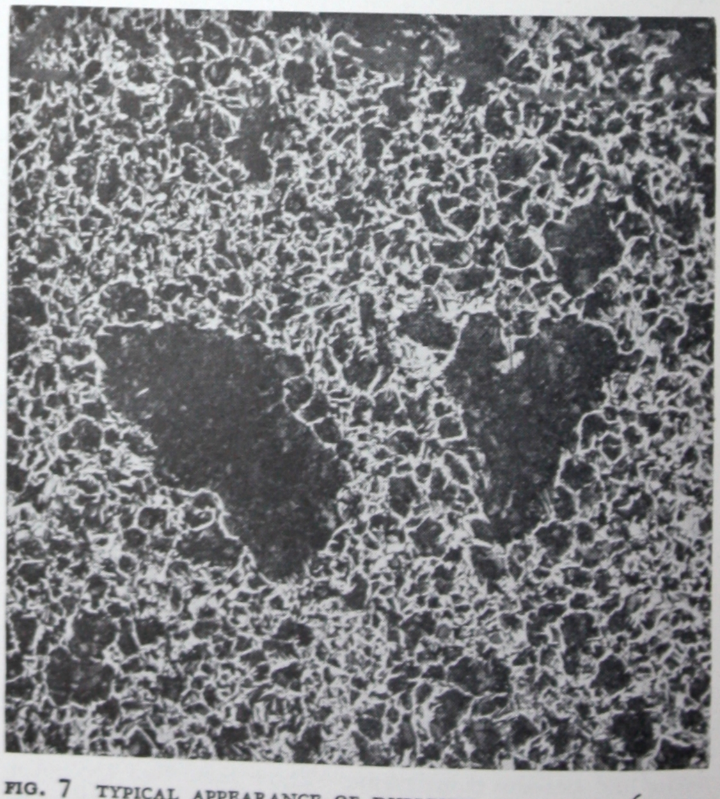

FIG. 7 TYPICAL APPEARANCE OF DUPLEXED GRAIN SIZE (MIXED GRAIN SIZES) IN 0.38 C STEEL, ×100

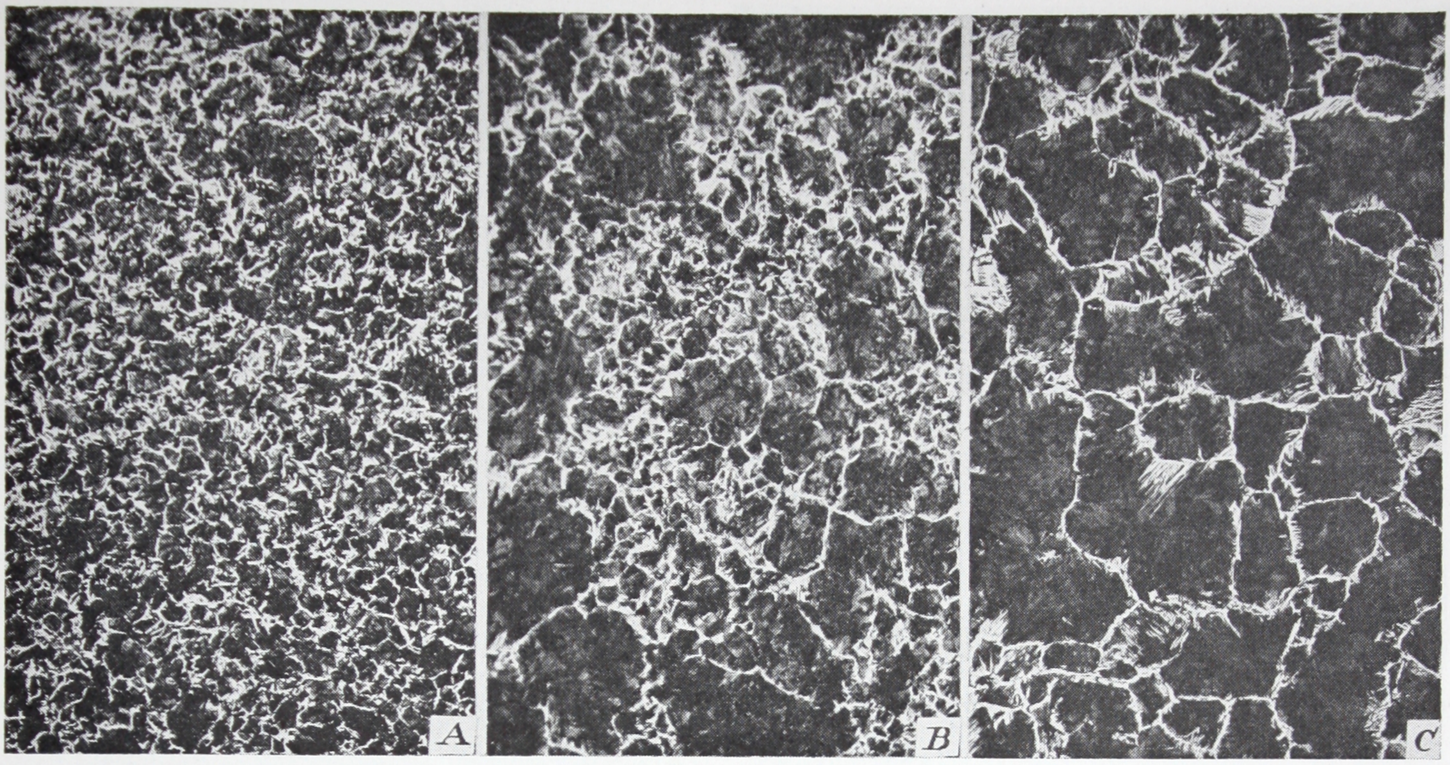

FIG. 8 GROWTH OF AUSTENITE GRAINS WITH TIME AT TEMPERATURE IN 0.38 C STEEL
(Heating temperature = 1625 F (885 C); for *A*—10 min; *B*—30 min; *C*—4 hr.)

in common use, the McQuaid-Ehn carburizing test, differs to such an extent from all the others in principle and technique that it does not always, or necessarily, yield the same result and requires special interpretation. There is no doubt that much of the confusion existing today originates in this fact. Let us therefore examine the methods in some detail and see why the metallurgist, trying to be precise, finds difficulty in avoiding such expressions as McQuaid-Ehn grain size, true austenite grain size, and actual grain size.

The methods commonly used can be classified as (*a*) those which change the chemical composition of the metal in the process of marking out the boundaries of the austenite grains, and (*b*) those based on the fact that under appropriate conditions of cooling, the austenite grains on transforming leave behind "footprints" which disclose their size.

The McQuaid-Ehn carburizing method: This consists of pack-carburizing the steel at 1700 F (925 C) for eight hours, followed by slow cooling (4–5 F per min) to room temperature. The metallurgical principle involved is that when austenite containing more than about 0.8 per cent carbon is cooled slowly, the carbon in excess of that amount separates out at the austenite grain boundaries in the form of a thin network of iron carbide, as seen in Figs. 4*C*, 16*A*, and 16*B*. The chief merit of this method is that when applied to steels intended for service in the case-carburized condition, it duplicates closely the commercial conditions and yields valuable information as to depth of case, grain size, presence of soft spots, and the normality and abnormality of the case, of which more will be said later; on the other hand, when the method is applied to steels other than the carburizing grades, it requires cautious interpretation for the following reasons: (*a*) Since the composition of the steel is altered by the introduction of carbon and oxygen, the grain size observed is not necessarily that of the original metal; (*b*) since the method calls for eight hours at 1700 F in the carburizing box, the resulting grain size it discloses is not necessarily that which the steel would have when heat-treated for service at lower temperature and for a shorter time; (*c*) since the carbon content of the case differs from that of the core, two entirely different austenite grain sizes are frequently found in one specimen. In short, the only unequivocal information obtainable from this test is whether the grains coarsen or not under the special conditions of the test, i.e., eight hours at 1700 F, with change in composition. In many instances this information is considered sufficient to classify a heat of steel as coarse- or fine-grained, but frequently it is of greater consequence to know the precise temperature at which a steel begins to coarsen in a desired time interval, or the grain size attained as a result of a given heat-treatment. Since the carburizing test cannot supply it, the metallurgist resorts to other methods.

The normalizing method: The normalizing method is one of the simplest and most widely used noncarburizing procedures. It consists of heating a specimen of suitable dimensions to the desired temperature for the desired length of time and cooling it in air. Its main limitation is that it is applicable primarily to steels containing between 0.30 and 0.55 per cent carbon, but in this carbon range it yields excellent definition of the austenite grains, as in Fig. 4*A*. It is based on the fact that in a steel containing less than 0.75 per cent carbon there is an excess of ferrite over the amount required to make pearlite which, when a suitable specimen is cooled at a moderately fast rate, separates out at the austenite grain boundaries forming a network. The method, therefore, uses ferrite as the medium to delineate the austenite grain pattern. It is not applicable to all steels because, when the carbon is more than 0.55 per cent the amount of free ferrite available may not suffice to form a complete network, and when the carbon is less than 0.30 per cent the ferrite is likely to separate out in large patches which do not clearly mark out the grains. But since the method can be carried out under any desired conditions of temperature and time, and since it does not alter the composition of the steel, it is not open to equivocal interpretations; it simply discloses the austenite grain size existing at the instant when cooling started. It is also applicable to high-carbon (hypereutectoid) steels in which case the grains are outlined by an iron-carbide network.

The gradient-quench method: Inasmuch as many steels of

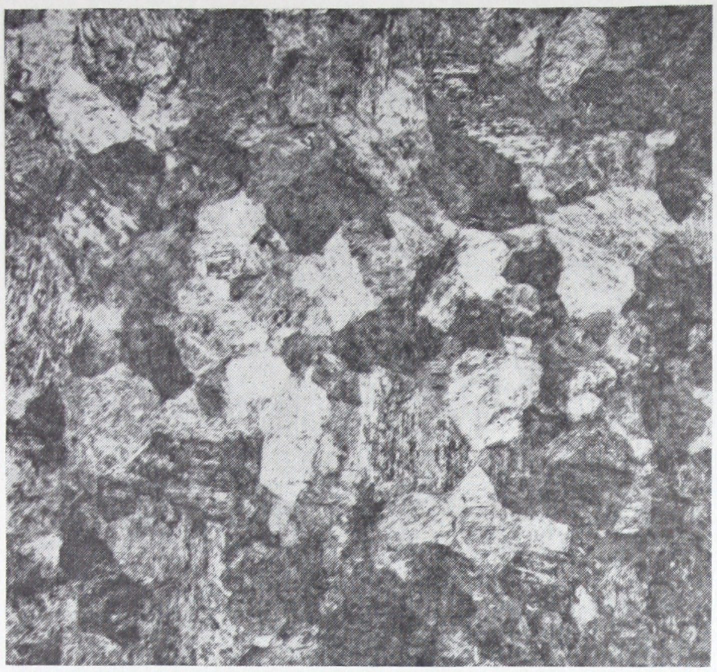

FIG. 9 AUSTENITE GRAIN PATTERN AS REVEALED IN TEMPERED MARTENSITE BY SPECIAL ETCHING REAGENT, 0.40 C STEEL, ×100

great commercial importance are outside the range of carbon content covered by the normalizing test other methods had to be found to ascertain their austenite grain size. The "gradient-quench" method fills this need. It is essentially a means of obtaining automatically the cooling rate which yields the best definition of the austenite grain pattern. It is carried out as follows: A specimen of adequate dimensions (generally $^1/_4 \times {}^1/_2 \times 2$ in.) is heated under the desired conditions of temperature and time and cooled by immersing in water about one fourth or one third of its length, allowing the remainder of the piece to cool in air. In this manner a gradient of cooling rates is obtained along the length of the specimen. If a 0.20 per cent carbon steel is thus treated and examined microscopically in longitudinal section, the following sequence of structures is found: (*a*) In the portion cooling under water, martensite; (*b*) in some portion of the metal cooling in the vicinity of the surface of the water, martensite and a network of nodules of extremely finely laminated pearlite which outlines the austenite grains, as illustrated in Figs. 5*A*, 5*B*, 5*C*, and 5*D*; and (*c*) in some region near the top of the specimen, pearlite and a network of ferrite marking out the austenite grain pattern.[5]

If the method is applied to steels containing more than 0.55 per cent carbon, the ferrite network will be missing but a network of dark-etching fine pearlite will be visible; in very high-carbon steels (more than 1 per cent carbon) a network of iron carbide is present. Thus in all cases the method develops one or more areas where the austenite grain boundaries are clearly marked out.

The martensite etching method: It happens sometimes, though rarely, that neither the normalizing, the gradient-quench, nor the carburizing methods yields a satisfactory definition of the austenite grains. In that event the metallurgist may resort to an etching reagent possessing the ability to show

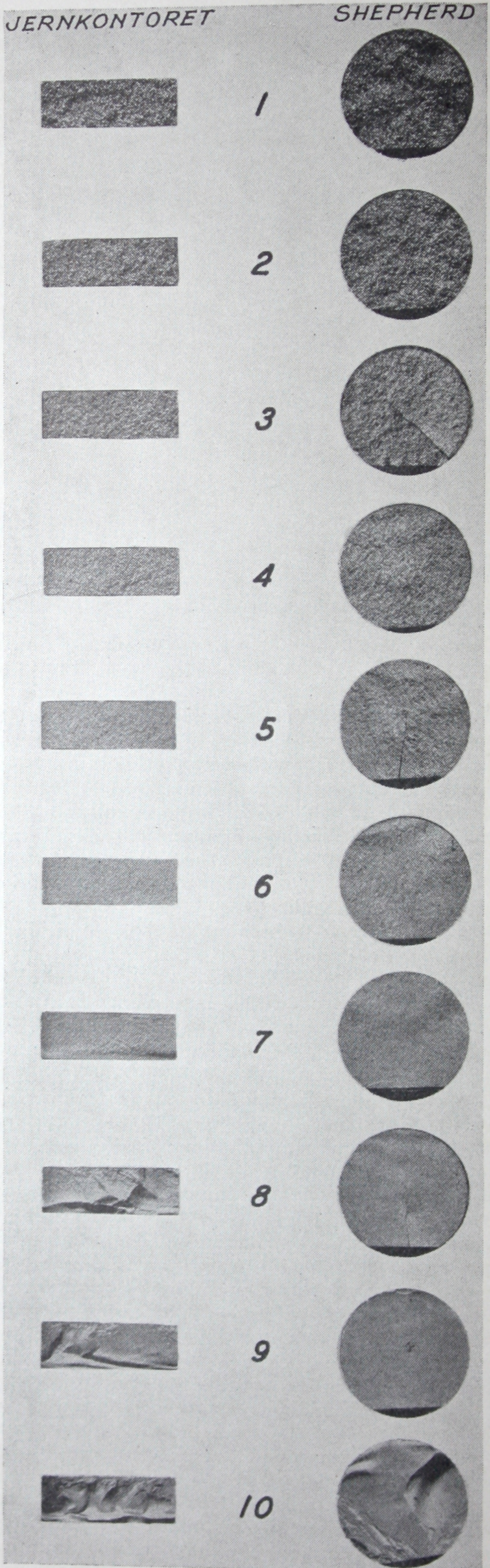

FIG. 10 TWO SETS OF STANDARD FRACTURES FREQUENTLY USED

the austenite grain pattern in steels which have been quenched and tempered slightly (15–30 min at 450–600 F is usually sufficient). This reagent is prepared by dissolving in 100 cc of ethyl alcohol 1 gram of picric acid and 5 cc of concentrated hydrochloric acid. Its action is based on the fact that when austenite transforms to martensite as the result of a drastic quench, the relative orientation of the austenite grains at the heating temperature is not lost completely during the transformation and therefore can be shown by an etching reagent of sufficient sensitivity to differentiate between differently oriented grains. The method is applicable to plain carbon and alloy steels over a wide range of compositions. It can also be used to determine the grain size in the martensitic section of a gradient-quench specimen.

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[5] The gradient-quench method was used to obtain the following illustrations in this paper: Figs. 5*A*, 5*B*, 5*E*, and 5*F* in which the austenite grain size is outlined by a network of fine pearlite. The ground mass is martensite. Fig. 7, Figs. 8*A*, 8*B*, and 8*C*, Fig. 12*A*, and Figs. 13*A* and 13*C*; in these the austenite grains are outlined by a network of ferrite. The ground mass is darkly etched pearlite in all except Fig. 13*C*, where it is darkly etched martensite.

Fig. 9 is a typical photomicrograph of the austenite pattern as revealed by this method. This pattern, which does reveal the prior austenite grain size and is significant in respect to the properties of the steel, may to one not versed in metallography look somewhat like the pearlitic structure in Fig. 4*B*, which does not reveal the austenite grain size and is not significant for our present purpose. The composition and thermal history of the specimen must be known before one can tell whether what is seen under the microscope as an "apparent grain" is or is not a true "footprint" of the prior austenite grains. It sometimes happens that the composition and commercial treatment of a steel are such that the significant prior austenite grain size can be immediately deduced from its microstructure, but this only occurs in rare cases. In the far more common cases where nothing can be told about the austenite grain size without special test, one of the methods described herein must be resorted to if the information is to be secured.

The fracture method: In the fracture method (4, 5), probably the oldest but still a dependable one, a notched specimen of adequate dimensions is quenched drastically from any desired temperature in the austenite range, broken at the notch, and the coarseness of its fracture rated by comparison with a standard set of fractures. There is, however, one all-important precaution to observe: Only the fully hardened, or martensitic, part of the test bar must be considered. In specimens which do not harden to the center, and many do not, there is a pearlitic core whose fracture is not indicative of the austenite grain size, and must be disregarded. The method is best adapted to medium- and high-carbon steels. Fig. 10 represents the two sets of standard fractures most commonly used. It is of interest to note that the two sets are practically identical and graded in steps which, by a happy coincidence, match well the corresponding steps in the standard A.S.T.M. grain-size charts.

Heat-etching method: One limitation common to all the noncarburizing methods available today is their inability to reveal satisfactorily the austenite grain size of steels containing less than 0.10 per cent carbon. This gap is now closed for a technique has been evolved (6) which is applicable to plain carbon and alloy steels of all carbon contents, from a trace to hypereutectoid[6] compositions. The heat-etching method is based on the fact that when a polished steel surface is heated in an atmosphere which is not oxidizing, deoxidizing, carburizing, or decarburizing, the grain boundaries present at the temperature of the test are delineated, presumably by preferential vaporization of the metal at the grain boundaries, without perceptibly altering the chemical composition of the steel. Dry purified hydrogen or nitrogen is a satisfactory atmosphere for the purpose. After the polished specimen is heated to any desired temperature in the austenite range for a desired length of time, it is quenched, preferably in mercury, to prevent oxidation and staining of the polished and etched surface. Fig. 11*A* illustrates the austenite grain pattern of a 0.07 per cent carbon steel heated 10 min at 1900 F, and Fig. 11*B* that of a 0.66 per cent carbon steel after two hours at 2000 F, as revealed by the heat-etching method.

Other methods: In addition to those described, several other methods (7) based on oxidation or decarburization of the austenite grain boundaries are also used. While they also alter the composition of the metal, although to a much less significant extent than the McQuaid-Ehn carburizing method, they are not restricted by temperature and time specifica-

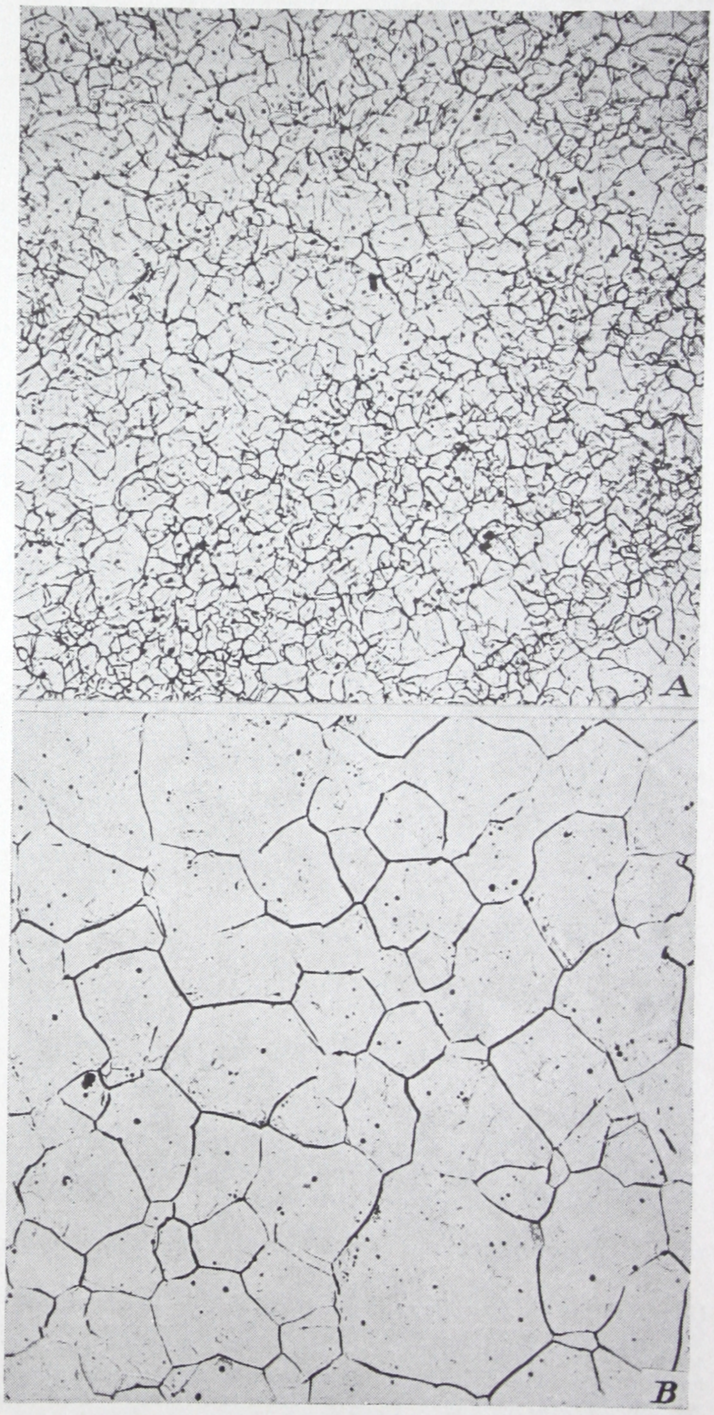

FIG. 11 AUSTENITE GRAIN SIZE AS REVEALED BY THE HEAT-ETCHING METHOD, ×100

(Fig. *A* is 0.07 C steel heated 10 min at 1900 F (1036 C) and quenched in mercury. Fig. *B* is 0.66 C steel heated 2 hr at 2000 F (1093 C) and quenched in mercury.)

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[6] The terms hypereutectoid, eutectoid, and hypoeutectoid are used to denote, respectively, carbon steels containing more than 0.75 carbon, just 0.75 per cent carbon, and less than 0.75 per cent carbon. The eutectoid composition is affected by the presence of alloying elements.

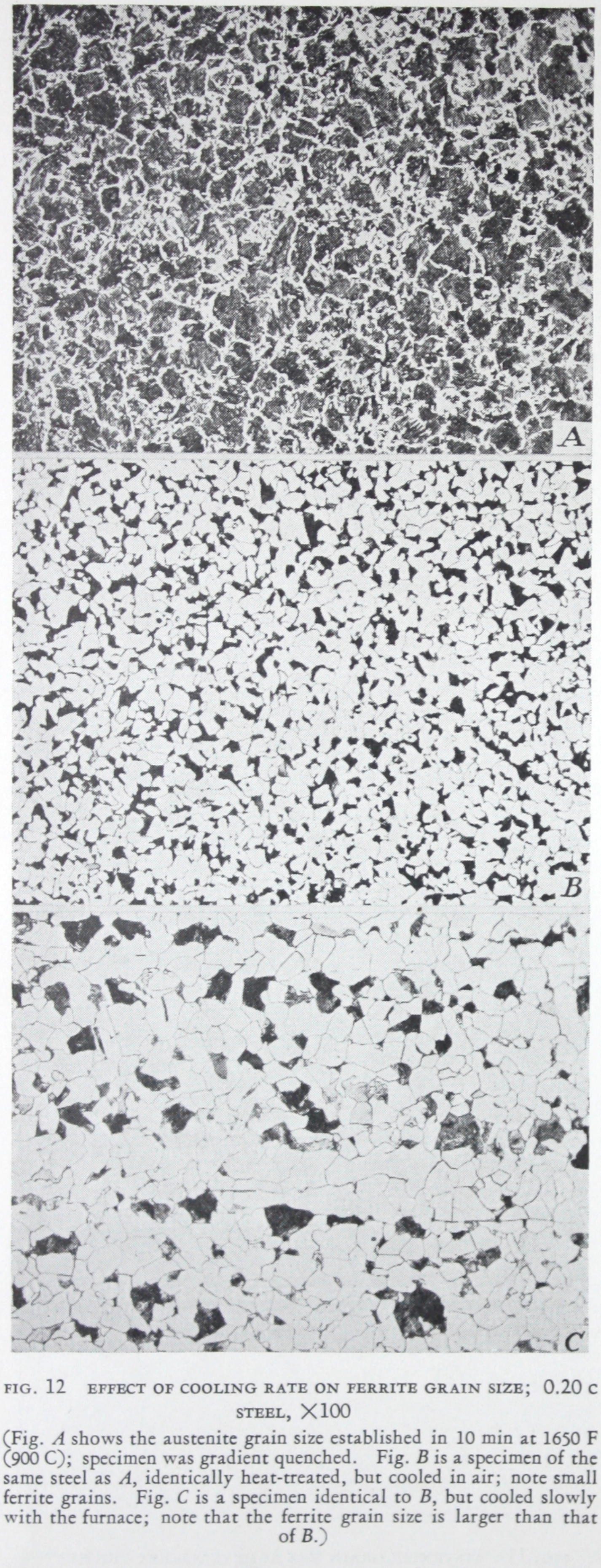

FIG. 12 EFFECT OF COOLING RATE ON FERRITE GRAIN SIZE; 0.20 C STEEL, ×100

(Fig. *A* shows the austenite grain size established in 10 min at 1650 F (900 C); specimen was gradient quenched. Fig. *B* is a specimen of the same steel as *A*, identically heat-treated, but cooled in air; note small ferrite grains. Fig. *C* is a specimen identical to *B*, but cooled slowly with the furnace; note that the ferrite grain size is larger than that of *B*.)

tions. The only reason why they are not described more fully here is because they do not illustrate any point essential to the purpose of this article.

6 *The Ferrite Grains.* Up to this point the discussion has dealt with the size of the austenite grains which existed at the maximum temperature of the heat-treatment. Now let us briefly consider what is known about the ferrite grains and the effect of their size on the properties of steel.

When free ferrite occurs in medium-carbon steel its mere presence and its distribution are generally of greater significance than its grain size; in very low-carbon steel the ferrite grain size is of considerable importance. Because it is difficult in steels containing more than about 0.05 per cent carbon to alter the ferrite grain size by heat-treatment without at the same time altering the size, shape, and distribution of the carbide particles, it has been very difficult to isolate the effect of ferrite grain size on the properties of steel. However, it is known in a general way that, other factors being equal, small ferrite grains contribute hardness, toughness, and strength at ordinary temperature. The size of the ferrite grains also seems to be a factor influencing such properties as deep-drawing quality, resistance to impact at low temperature, creep strength at high temperature within the ferritic range, the electrical properties of special steels such as the low-carbon high-silicon grade, and the yield point of very low-carbon materials (8).

Concerning the growth of ferrite grains at temperatures below the transformation range, it is known to be slow, except in low-carbon steels which have received a so-called "critical" amount of cold deformation. The exception, however, is of considerable interest. In a case recorded by Sauveur (9), specimens of 0.05 per cent carbon steel which were deformed in tension by loads of 38,000, 40,000, 42,000, and 44,000 lb per sq in. and then heated seven hours at 1200 F (650 C) developed different ferrite grain sizes. No appreciable grain growth occurred in the specimen loaded to 38,000 lb per sq in. and only a slight one in those loaded to 42,000 and 44,000 lb per sq in., but in that loaded to 40,000 lb per sq in. an exaggerated grain growth took place. From this and other experiments it was concluded that there is a critical strain which produces abnormally large ferrite grains. Subsequent investigations showed that, within limits, for each degree of cold deformation there is a temperature at which rapid ferrite grain growth occurs. It has also been reported (10) that exaggerated ferrite grain growth occurs when low-carbon steel is heated to 1375–1450 F, provided the metal has been air-cooled previously from 1850 F or higher.

7 *Relation Between the Austenite and Ferrite Grain.* It has been observed that for the same cooling rate, the larger the size of the parent austenite grains, the larger the ferrite grains tend to be. This trend is not difficult to demonstrate when specimens of different austenite grain sizes are cooled at the same slow rate, as shown in Figs. 13*A*, 13*B*, 13*C*, and 13*D*. However, when specimens of low-carbon steel made up of large austenite grains are cooled at a moderately fast rate, as, for example, small specimens air-cooled, the ferrite separates out at the crystallographic planes of the austenite crystals in the form of elongated or acicular areas, which may consist of one or more ferrite grains, alternating with areas of pearlite of the same general shape to form a pattern known as the Widmanstätten structure. In this type of structure it is not always possible to determine accurately the ferrite grain size, but it is unquestionably much finer than the ferrite grain size produced by the slow cooling of austenite grains of the same size. This is clearly shown in Figs. 14*A* and 14*B*, obtained from identical specimens of the same large austenite grain size cooled respectively with the furnace and in the air.

Small austenite grains, on the other hand, can be cooled slowly, or even comparatively fast, without forming the Widmanstätten structure, such as shown in Fig. 12. It is possible therefore, by cooling at a moderately fast rate, to obtain ferrite areas of practically the same size, both from coarse austenite

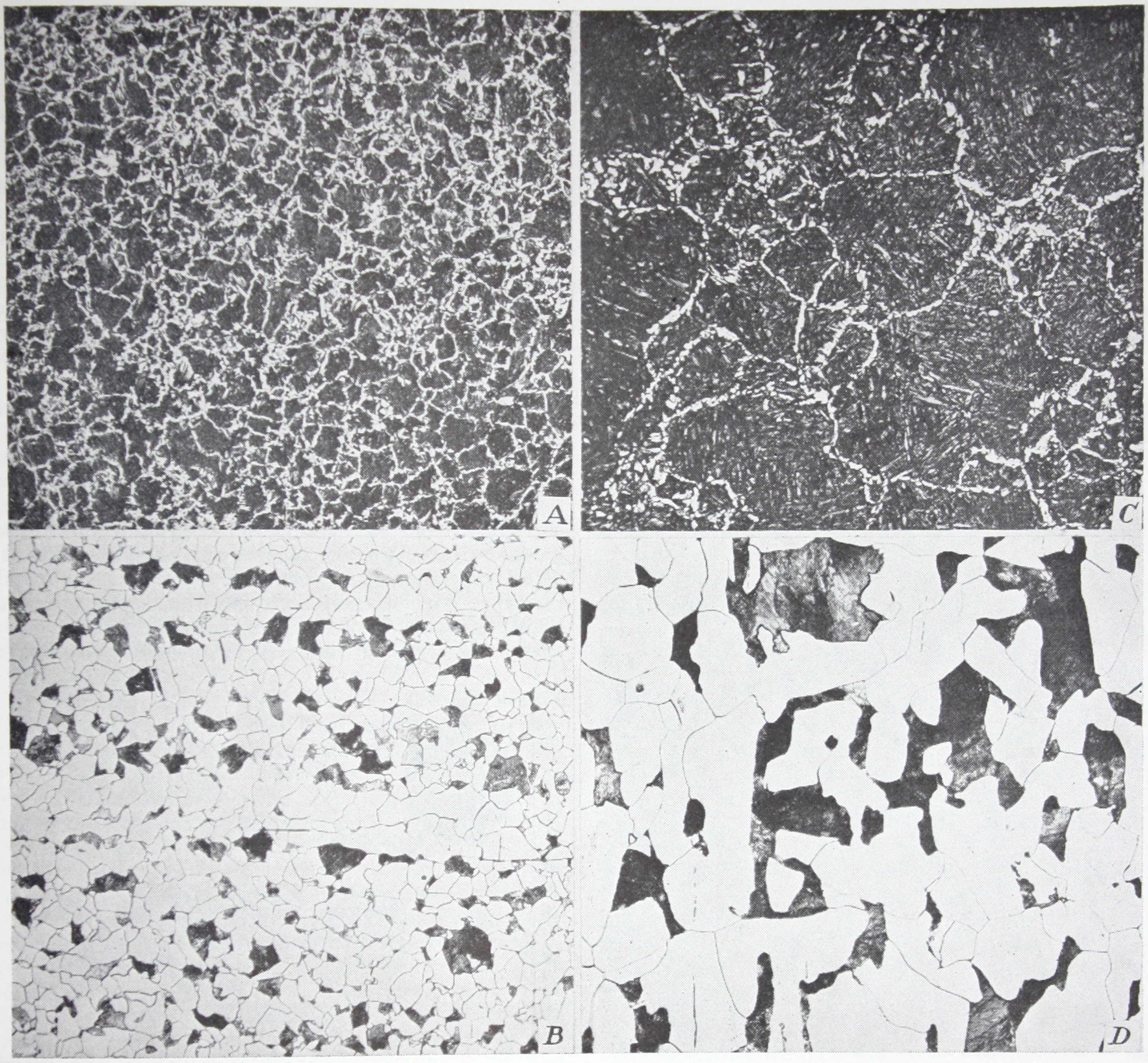

FIG. 13 EFFECT OF AUSTENITE GRAIN SIZE ON FERRITE GRAIN SIZE; 0.20 C STEEL, ×100

(Figs. *A* and *C* show austenite grain size established by heating *A* for 10 min at 1650 F (900 C) and *C* for 10 min at 2000 F (1095 C). Figs. *B* and *D* show ferrite grain size obtained by cooling at approximately the same rate (slowly with the furnace) two specimens treated identically to *A* and *C*. Observe that for the same cooling rate through the transformation range, the larger austenite grains transformed to larger ferrite grains.)

grains which transform to the Widmanstätten structure and from finer austenite grains which transform to more nearly equiaxed ferrite grains and pearlite areas. It is well to add at this point that whatever differences in physical properties are observed between the Widmanstätten and the more nearly equiaxed structures cannot be ascribed to difference in ferrite grain size; it is highly probable that the significant factor in determining the properties of the steel is the shape and distribution of the pearlite areas, that is, the structure of the steel.

The influence of austenite grain size and rate of cooling through the transformation range on the size of the ferrite grains can be summarized as follows:

(*a*) It appears that the ferrite grain size produced as the steel cools through the transformation range rarely, if ever, exceeds the grain size of the parent austenite.[7]

(*b*) The slower the cooling rate through the transformation range, the more closely does the ferrite grain size approach the size of the parent austenite grains.

(*c*) The tendency to form the Widmanstätten pattern, in which the ferrite grain size is probably small, appears to increase first with the size of the parent austenite grains for a given cooling rate through the transformation range, and second with the speed of cooling through the transformation range for a given austenite grain size.

These trends are shown schematically in Fig. 15.

"PEARLITE GRAINS" AND THEIR RELATION TO THE AUSTENITE AND FERRITE GRAINS

Even though occasional references to "pearlite grains" appear in the literature, the concept of a pearlite grain is difficult to reconcile with the definition of the word grain which postulates a crystalline unit of a single phase within which its atoms are arranged in a single orientation. Because pearlite is a lamellar aggregate of two phases, it seems preferable to refer

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[7] A possible exception to this rule is highly purified iron, in which large ferrite grains are said to form from small austenite grains.

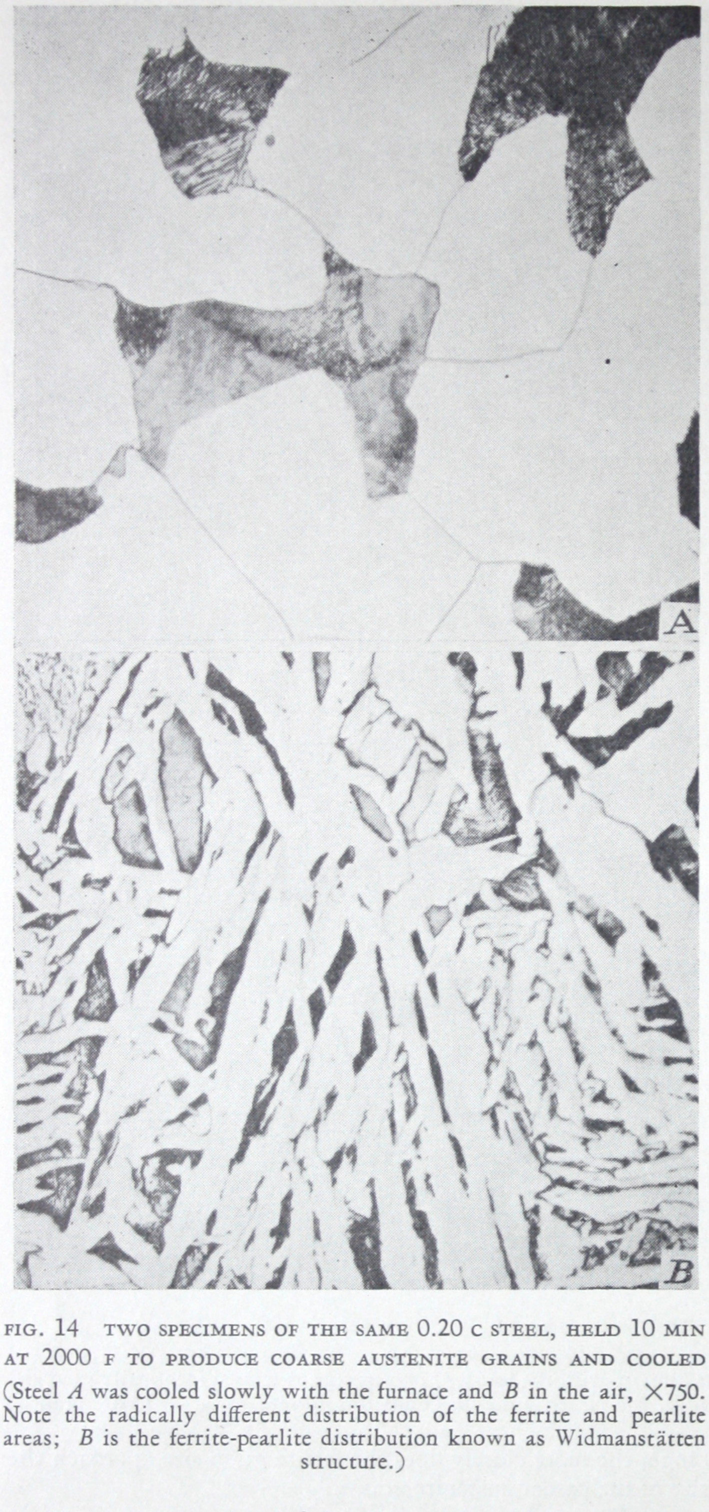

FIG. 14 TWO SPECIMENS OF THE SAME 0.20 C STEEL, HELD 10 MIN AT 2000 F TO PRODUCE COARSE AUSTENITE GRAINS AND COOLED

(Steel *A* was cooled slowly with the furnace and *B* in the air, ×750. Note the radically different distribution of the ferrite and pearlite areas; *B* is the ferrite-pearlite distribution known as Widmanstätten structure.)

to the pearlitic portions of the structure in such terms as pearlite "areas," "regions," or "patches." These pearlite regions must not be confused with the pearlite *colonies* previously mentioned; by a pearlite colony we mean any portion of a pearlite area which appears to be made up of a group of similarly oriented lamellae. The difference between what we are here calling pearlite areas and the colonies comprised in those areas is illustrated in Fig. 17.

The size of the pearlite regions depends largely on the carbon content of the steel and on the rate of cooling through the transformation range. In steels containing between approximately 0.10 and 0.30 per cent carbon, the pearlite areas, as seen microscopically, and ferrite grains are of nearly the same size, as can be seen in Figs. 12*B*, 12*C*, 13*B*, 13*D*, and 14. It will be observed in these photomicrographs that the pearlite areas and ferrite grains maintain their relative size even when their absolute size is changed by varying the cooling rate.

In steel containing between approximately 0.35 and 0.55 per cent carbon, the size of the pearlite areas increases with the rapidity of cooling through the transformation range and with the size of the parent austenite grains. This is the same as saying that there is less ferrite in a given steel specimen when it is cooled rapidly than when cooled slowly, and for a given cooling rate when the parent austenite grains are coarse than when they are fine.

While the factors influencing the size of the pearlite colonies have not been sufficiently investigated to warrant a categorical statement, there are reasons to believe that their size depends both on the cooling rate through the transformation range and on the size of the parent austenite grains, that is, slow cooling and large austenite grains promote the formation of large pearlite colonies.

Inherent Grain Size. This term "inherent grain size" has been used to denote the austenite grain size developed by the McQuaid-Ehn carburizing method as if it were a definite characteristic of the steel, but what has been said up to this point should suffice to show that there is no such thing as an inherent grain size. A steel may be said to possess as an inherent attribute a greater or a lesser tendency to resist coarsening when held at a given temperature for a given period of time, but certainly there is no size of the austenite grains which can be considered a fixed characteristic of a heat of steel. Even its coarsening temperature is variable and it has been found to be influenced

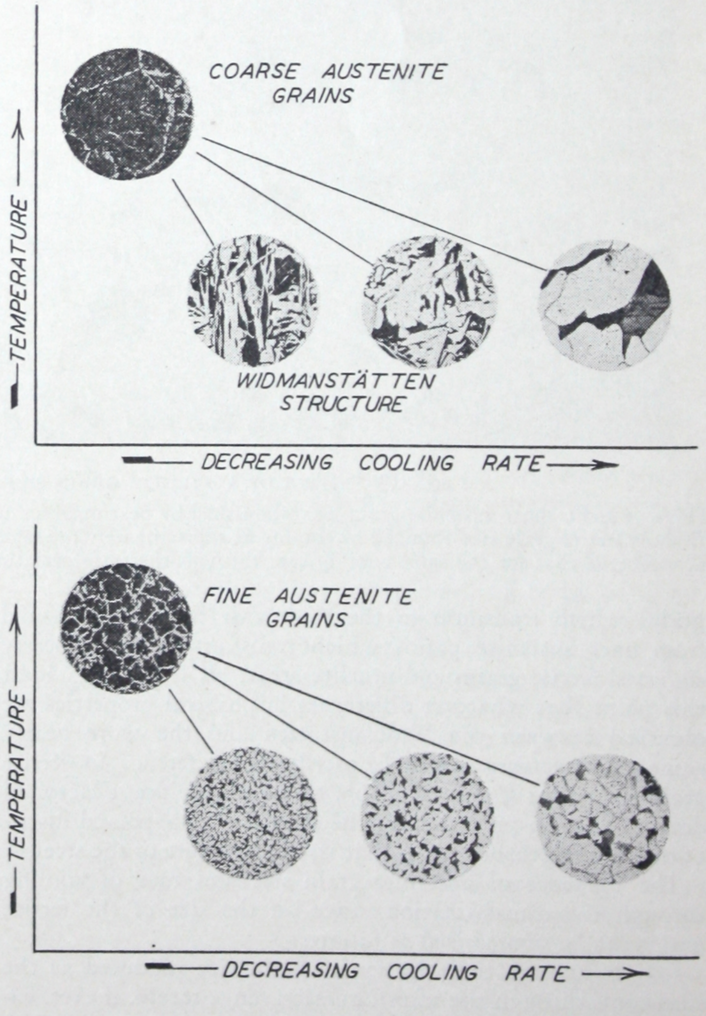

FIG. 15 SCHEMATIC REPRESENTATION OF THE INFLUENCE OF RATE OF COOLING THROUGH THE TRANSFORMATION RANGE AND SIZE OF THE PARENT AUSTENITE GRAINS ON THE SIZE OF THE FERRITE GRAINS AND ON THE FORMATION OF WIDMANSTÄTTEN STRUCTURE

by factors such as time at temperature, rate of heating, finishing temperature, degree of hot and cold reduction, prior structure.

Actual or Existing Grains. A complaint often voiced by men not versed in steel metallography is that the metallurgist is too much concerned with the nonexistent austenite grains and not with the actual or existing grains. Since this complaint is in itself an expression of the confusion existing in matters pertaining to the grain size of steel, it may be of some value to consider some of the possible interpretations which may be given to these phrases.

When a specimen of steel is polished, etched, and examined microscopically, the observer is confronted with a structure in which granular subdivisions, i.e., grains, may or may not be visible. If grains are visible these are, obviously, the actual or existing grains; if the material is largely ferrite, the grain size is that of the ferrite. The structure may, however, be made up of pearlite colonies or "footprints" of the austenitic grains which existed at the maximum temperature above the transformation range to which the steel was last heated. (Since it would be exceedingly cumbersome to have to resort always to long phrases such as "footprints or traces of the parent austenite grains," these are sometimes for convenience referred to as austenite or austenitic grains.) The fact to bear in mind is that although the solid-solution austenite no longer exists as such in plain carbon steels at room temperature, the grain pattern established while the steel was austenitic is very often the actual or existing grain structure observed under the microscope.

It is of the utmost importance to anyone concerned with the grain size of steel to be able to identify the kind of grains present in a structure, for the factors which determine the size of the austenite grains are not the same as those which determine the size of the ferrite grains. Likewise, the properties of steel influenced by the size of the austenite grains are different from those influenced by the ferrite grain size. For these reasons it may be profitable to consider factors determining what type of grain is likely to be present in a given steel specimen.

In plain carbon steels containing from traces to about 0.25 per cent carbon in the as-rolled, as-annealed, or as-normalized conditions, the existing or readily detectable grains are ferrite grains. The reason for this is that in these steels the areas of free ferrite are sufficiently large to disclose the ferrite grain size clearly, but sometimes too large to make a satisfactory network for outlining the austenite grains; this can be observed in Figs. 12*B*, 12*C*, 13*B*, 13*D*, and 14*A*.

In medium-carbon steels (0.35–0.55 per cent) similarly treated, the existing grain pattern that is the most likely to be readily detectable is that of the austenite grains, because in this carbon range the amount of free ferrite which separates at the austenite grain boundaries during the transformation is approximately right to make a satisfactory network. However, with proper preparation of the metallographic specimen it is sometimes possible to bring out, in addition to the austenite grain pattern, a few ferrite grain boundaries within the ferrite areas, and a more or less satisfactory definition of the pearlite colonies, as is shown in Fig. 4*A*.

In steels containing from about 0.75 to about 1 per cent carbon in the as-rolled, as-annealed, or as-normalized conditions, it is extremely difficult, if at all possible, to estimate the former austenite grains, because there is not sufficient separation of either ferrite or iron carbide to mark out the network. What some have called existing grains in these steels can only be pearlite colonies, though these are detectable only in correctly prepared specimens, as in Fig. 4*B*.

In steels containing more than 1 per cent carbon, in the as-rolled, normalized, or annealed conditions, the existing grain pattern is that of the parent austenite grains. In these steels there is a sufficient amount of carbon to form a network of free iron carbide around the austenite grain boundaries. In carefully prepared specimens it is also possible to see the pearlite colonies, as, for example, in Fig. 4*C*.

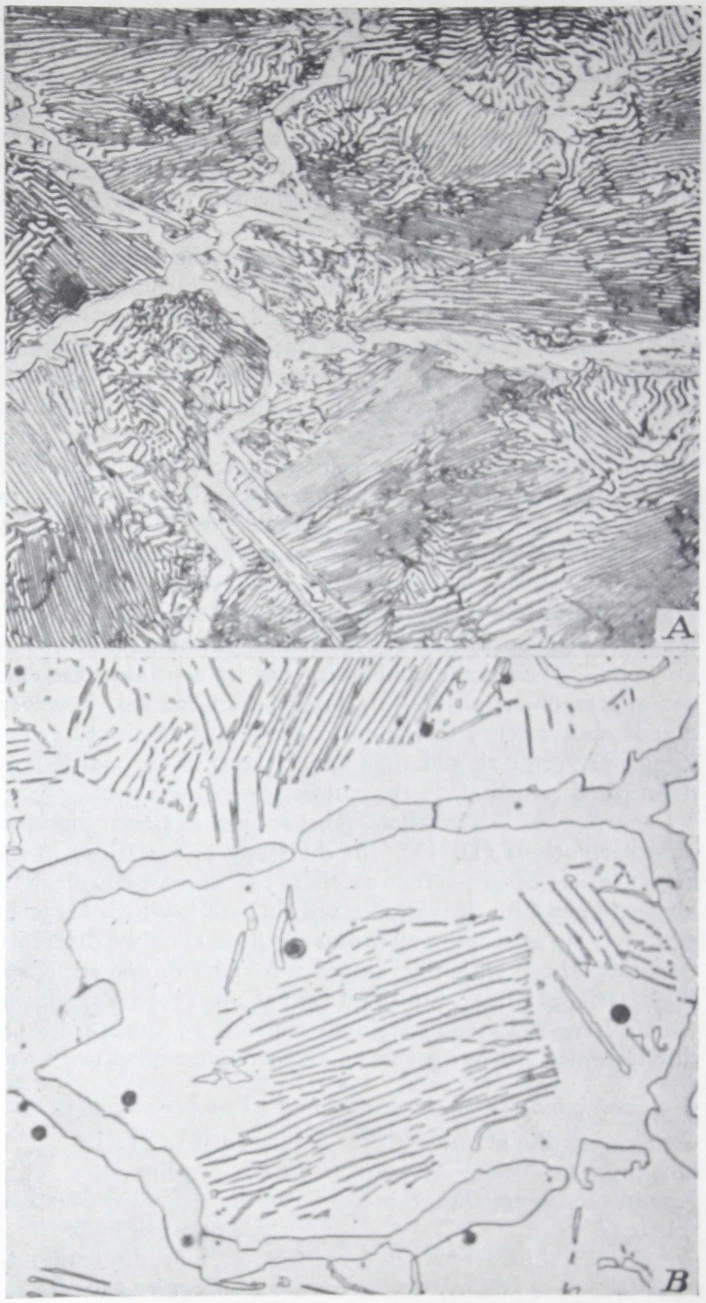

FIG. 16 THE STRUCTURAL CHARACTERISTICS OF A SO-CALLED NORMAL STEEL IS SHOWN IN *A*; *B* SHOWS THOSE OF A SO-CALLED "ABNORMAL" STEEL, ×1000

Generally, no grains are detectable in a steel which has been cooled from above its transformation range at a rate sufficiently fast to make it 100 per cent martensitic, unless the specimen is tempered and etched as described previously, in which case the austenite grains are revealed. (Compare Figs. 3 and 9.) However, when a specimen is cooled from above its transformation range at a rate slightly slower than that required to make the steel 100 per cent martensitic, some nodules of finely laminated pearlite are likely to be formed at the austenite grain boundaries, as in Fig. 5. In this case the existing or readily visible grain pattern is again that of the prior austenite.

The expression "actual austenitic grain size" is sometimes used to bring out clearly the fact that a determination of the austenite grain size was made on the steel specimen when subjected to the same time and temperature in the austenitic range as in the heat-treatment applied in the preparation of the steel for its commercial use, in contradistinction to the time, temperature, and environment specifications of the McQuaid-Ehn carburizing test.

The term "carbide grain size" has occasionally been used, apparently to denote areas comprising particles of carbide; however, it is a misleading term, as the only real carbide grains are the individual particles of carbide.

Summarizing the preceding remarks on the use of such expression as actual, existing, inherent, and carbide as applied to the grain size of steel, it may be said that:

(*a*) Inasmuch as alternative phrases of perfect explicitness, such as austenitic or ferritic grain size have always been available, the use of less precise phraseology has introduced unnecessary ambiguity and at times cast doubt on the ability of the user of the term to identify type of grain to which he alluded.

(*b*) Since the concept of an "inherent grain" size is not supported by the experimental evidence now available, that expression is meaningless and its use is to be avoided.

(*c*) The use of the phrase "McQuaid-Ehn grain size" to denote the austenitic grain size obtained under standardized conditions (carburization at 1700 F for eight hours followed by slow cooling) carries no ambiguity and its continued use does not appear objectionable. It must be understood, however, that it always refers to the austenitic grains developed at one specific temperature and time under the special conditions of the method which alters the composition of the steel.

Normality and Abnormality. This subject has been discussed by other authors (11, 12). In the study of variations in the hardenability of low-carbon steels as case-carburized, made by McQuaid and Ehn, it was observed that steels which hardened uniformly on quenching after carburization could be differentiated from those which developed soft spots by the structural characteristics of the carburized case as observed on specimens which have been cooled slowly instead of quenched. On slowly cooled specimens these differences were noted:

Good hardenability	*Poor hardenability*
Coarse austenite grains	Fine austenite grains
Fine pearlite	Coarse pearlite
Pearlite contiguous to carbide network	Pearlite separated from carbide network by ferrite
Continuous, thin carbide network	Coarser, more discontinuous and irregular network

Some of these differences are clearly illustrated in Figs. 16*A* and 16*B*.

The structure of a steel capable of satisfactory hardening was thus referred to as being normal while that of a steel of poor hardening properties was said to be abnormal. The words might have been well chosen at the time to classify the steels intended for service as carburized, but in the meantime the test has been extended to other grades and the implication of desirable and undesirable properties still lingers when this terminology is used. The fact is that normality and abnormality as used by metallurgists today when referring to steel other than the carburizing grades in no sense imply good or poor quality. Each type possesses properties that make it preferable for certain specific purposes.

TABLE 2 INFLUENCE OF AUSTENITE GRAINS UPON STEEL BEHAVIOR

Property	Austenite grain size: Coarse	Austenite grain size: Fine
Hardenability	Deeper	Shallower
Tensile strength (steel normalized)	Higher	Lower
Ductility (steel normalized)	Lower	Higher
Impact strength	Lower	Higher
Carburized structure (McQuaid-Ehn test)	Normal	Abnormal
Machinability, rough	Improved	Impaired
Machinability, finish	Impaired	Improved
Transformation temperature	Lower	Higher
Quenching cracks	Frequent	Very rare
Grinding cracks	More susceptible	Less susceptible
Distortion in heat-treating	Greater	Less

Effect of Austenite Grain Size on Properties of Steel. An important effect of austenite grain size on the properties of steel is its effect on hardenability (13). The trend of the influence of size of the austenite grains (assuming constant composition of the steel) upon steel behavior is given in Table 2.

Estimation of Grain Size. The usual procedure for evaluating the austenite grain size of a specimen is as follows: The specimen is treated by one of the methods previously described, given a metallographic polish, etched with a suitable reagent, and the structure thus obtained projected on the ground glass of the microscope at a magnification of 100 diameters. Its grain size is determined by comparison with a standard chart.

Since the measurement is always made upon a plane surface the grain size reported always refers to the area of the cross section of the grains. The grain size is indicated by an index

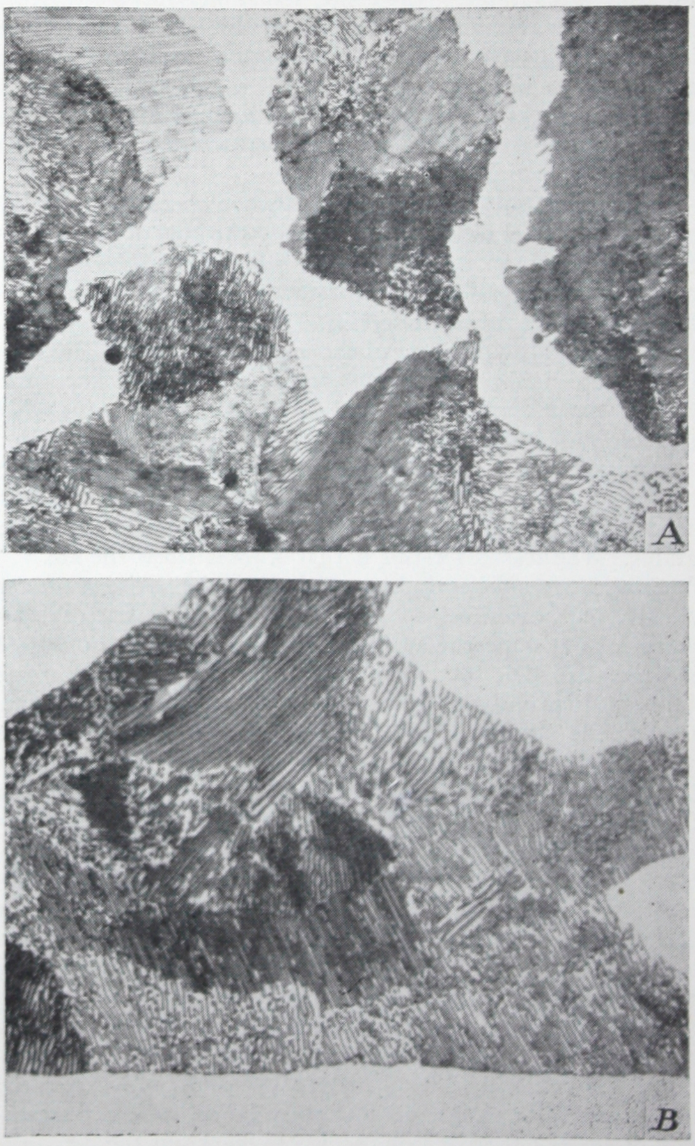

FIG. 17 PEARLITE AREAS AND COLONIES

(Fig. *A* shows the regions of pearlite surrounded by ferrite are the pearlite areas; the variously toned portions comprised within these areas, each made up of similarly oriented lamellae, are the pearlite colonies; normalized 0.45 C steel, ×750. Fig. *B* shows a single pearlite area within which several colonies are clearly discernible; normalized 0.20 C steel, ×1500.)

TABLE 3 GRAIN SIZE CORRESPONDING TO A.S.T.M. INDEX NUMBERS

A.S.T.M. grain-size number	Number of grains per sq in. at ×100 Mean	Maximum	Minimum
1	1	1.5	0.7
2	2	3.0	1.5
3	4	6.0	3.0
4	8	12.0	6.0
5	16	24.0	12.0
6	32	48.0	24.0
7	64	96.0	48.0
8	128	192.0	96.0

number which refers to the number of grains existing in one square inch of the image at a magnification of 100 diameters. The correlation of these index numbers with the actual number of grains per square inch of image at 100 magnification is given in Table 3.

The standard chart for carburized specimens (A.S.T.M. E19-33) consists of two series of photomicrographs representing the hyper- and hypoeutectoid portions of the case of case-carburized specimens, graded in eight steps which correspond closely to the calculated number of grains per square inch given in the preceding table. The corresponding chart (A.S.T.M. E19-38T) for all other specimens is a series of grain outlines graded in the same eight steps.

While a magnification of 100 diameters is generally used during the actual estimation at the microscope, a lower magnification is preferable for very coarse grains, or a higher magnification for the extremely fine grains sometimes found in alloy steels. The same chart is used to match the image, but in reporting the grain-size number the following rules must be observed: For each doubling of the 100 times magnification the grain size is reported as two more than that which it matches on the chart; for each halving of magnification, as two less than that matched on the chart. Thus, if a structure at ×400 matches the No. 2 grain size of the chart, its grain size is No. 6. If a match is found at ×50 with the No. 3 grain size of the chart, the grain size is reported as No. 1.

Effect of Alloying Elements on the Austenite Grain Size. In general, those elements added to steel which combine with carbon to form carbides, or with oxygen to form a finely divided dispersion of oxides, tend to enhance resistance to grain growth (14). The generally accepted explanation for this effect is that the carbides or oxides of these elements are capable of remaining both undissolved and unagglomerated over a considerable temperature range, and as long as they remain in this optimum condition they somehow provide an effective obstruction to grain growth. As soon as they dissolve, or coalesce to form larger particles, they cease to be effective inhibitors, and the grains then grow rapidly, often attaining a larger size than that observed at the same temperature in unalloyed steels.

Elements such as nickel or copper, which do not form carbides, do not seem to affect the grain size markedly.

Effect of Austenite Grain Size on the Rate of Transformation of Austenite. One of the most important contributions of austenite grain size to the properties of steel is its effect on the depth to which a given section hardens on quenching (hardenability) (15). Davenport and Bain (16) showed that the rate at which austenite transforms to ferrite and carbide is greatly influenced by the austenite grain size. Since the transformation on cooling generally begins at the austenite grain boundaries, it follows that a steel in which there is more boundary surface (fine austenite grains) will transform at a faster rate than one in which there is less boundary surface (coarse austenite grains). For reasons that are too lengthy to state in this review, a slow transforming steel can be made martensitic by cooling at a rate slower than that required for a steel which transforms more rapidly. In other words, coarse austenite grains require a less drastic cooling rate to form marteniste. This means that, on quenching, a given section of steel will harden to a greater depth when its austenite grains are coarse.

It is realized that this review has not touched upon all the aspects of the grain size of steel, nor discussed exhaustively those touched upon, but it is hoped that it has laid a foundation for more advanced reading by those interested in pursuing this subject. The various aspects of the austenite grain size of steel have recently been reviewed by Ward and Dorn (17) and Bastien (18). The reader is referred to these articles for a more detailed discussion of some points barely touched in this introduction to the subject and for an extended bibliography.

ACKNOWLEDGMENT

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